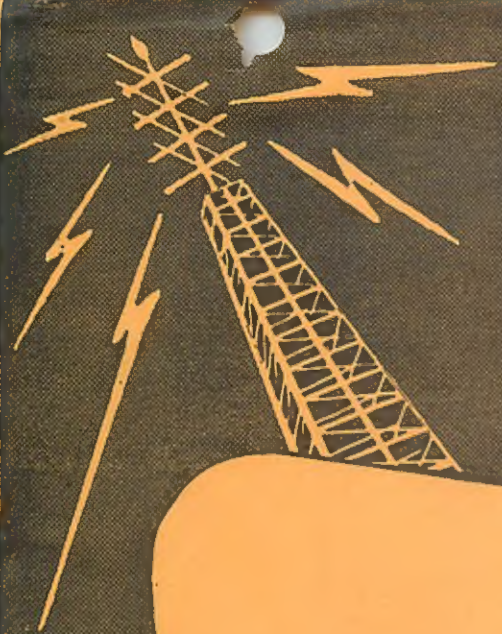
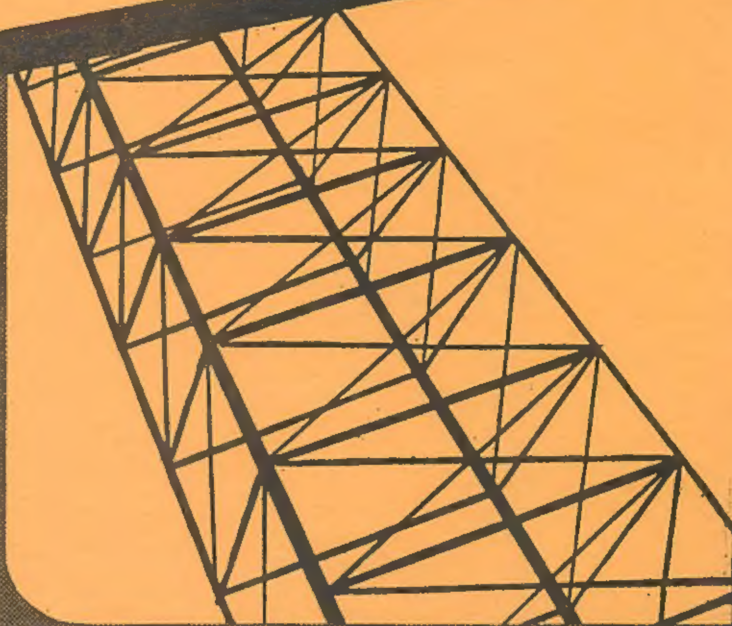


LESSON FTR - 28

FREQUENCY MODULATION TRANSMITTERS



DE FOREST'S RADIO ELECTRONICS TRAINING, INC.

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LESSON FTR-28

FREQUENCY MODULATION TRANSMITTERS

# # # # #

The secret of happiness is not in doing what one likes, but in liking what one has to do.

-- James M. Barrie

MODULATION

In our early explanations of Radio we told you that a frequency of 10,000 cycles per second was often considered as the dividing line between the Audio and Radio regions of energy. Thus, in general, the frequencies which we can hear, can not be transmitted directly through space, while those which can be transmitted will not affect our ears.

To be of practical benefit, the radiated or transmitted frequencies must be made to carry intelligence so that, at the receiver, they will produce an action which affects at least one of our senses. Due perhaps to its comparative simplicity, or similarity to the Telegraph, the early Radio systems were arranged to produce audible code signals and were known as a Wireless Telegraph.

In these early systems, the higher transmitted Radio frequencies had to carry lower or audio frequencies, and this was accomplished by starting and stopping the high frequencies according to a pre-arranged code. At the receiver, the reception of the high frequencies would cause a local circuit to be energized and thus a telegraph sounder could be operated.

Later, after vacuum tubes came into use, the heterodyne principle became popular and the generated frequency of an oscillator in the receiver, mixed with the incoming signal frequency, produced a beat note at an audible frequency. This principle is still used for code reception and the audible beat frequency operates head phones or loud speakers. However, the code is transmitted by starting and stopping the radiated high frequency at the desired intervals.

In general, the control of the radiated energy, enabling it to carry signals, is known as "modulation". Thus we have the control or "modulation" frequency and the radiated or "Carrier" frequency.

By the general methods first mentioned, a "Wireless" system can transmit messages similar to those of the wired Telegraph systems but Radio enjoys its present popularity because it can transmit messages of the same type as the Telephone.

For this type of signal, the high frequency carrier must be modulated by the audio frequency of the signal and thus, the original method of stopping and starting the carrier is not practical. Instead, the carrier is made to vary at the rate of the modulating frequency and present day systems can be classed according to the type of variation.

To explain the modulation methods of the older and more common systems, for Figure 1 we have drawn a simplified circuit of a Radio Frequency oscillator of the Electron Coupled Type.

As explained in the lesson on Oscillators, the values of condenser C and Inductance L control the frequency at which the oscillator operates. The tuned circuit, commonly known as a "tank" circuit made up of C_1 and L_1 in the plate circuit of the screen grid tube, may be adjusted to the same frequency as C-L or one of its harmonics. Coil L_2, inductively coupled to coil L_1, will contain a constant frequency which may be radiated or braodcast when properly connected to an antenna.

The basic principle of operation of Figure 1 is very similar to circuits previously explained. However, we want to offer greater detail with regard to the variations in order that you clearly understand the action of a simple transmitter.

Considering only the cathode, control grid and screen grid circuits of the tube, we have the basic arrangement of a triode Hartley Oscillator. In this instance, the screen grid serves as the plate.

As the instant power is supplied there will be a surge of screen grid (plate) current to the cathode, through the lower portion of L and back to B-. Acting as an auto-transformer, this change of current through a part of L induces an emf in the entire winding.

The polarity of this emf is such that the grid, coupled to the upper end of the coil through condenser C_g, becomes more positive in respect to the cathode and causes a further increase of screen grid current. However, as soon as the grid becomes positive, there will be grid current which carried by resistor R_g produces a voltage drop that tends to make the grid negative in respect to the cathode.

This action continues until the opposing voltages become balanced at which point there is no further change of grid potential, the screen grid current does not vary and the induction in coil L dies out. With no induced emf to maintain the positive grid potential it diminishes in value, the grid becomes less positive or more negative, and causes a reduction of screen grid current.

During the period of increasing screen grid current, condenser C is charged to the voltage across the entire coil L and, as the emf dies out, the condenser discharges through the coil causing a reduction of tank circuit voltage. As mentioned above, this reducing voltage lowers the positive grid potential to cuase a reduction of screen grid current.

With reducing screen grid current, the magnetic flux around coil L becomes weaker or collapses and reverses the direction of induction, thereby aiding the discharge of the condenser. Thus, the grid becomes more negative, the reduction of screen grid current continues and the resulting induction not only discharges the condenser completely but charges it with a voltage of opposite polarity.

This action continues until the grid potential is sufficiently negative to cut off the screen grid current and the magnetic flux, set up by coil L, is reduced to zero. With zero flux, the induction dies out, the condenser starts to discharge and the grid potential becomes less negative, thereby, allowing the re-establishment and increase of screen grid current. With increasing screen grid current, the action is as previously explained and the complete cycle is repeated.

The speed at which the changes occur depends upon the values of coil inductance and the condenser capacity which thereby regulates the rate at which the complete changes take place and control the frequency of the oscillator.

As shown in Figure 1, the plate of the tube connects to a separate supply terminal usually of higher voltage than that of the screen grid. Therefore, many of the emitted electrons will pass through the screen grid mesh and reach the plate, but the previously explained action of the control grid voltage will vary the stream of electrons at the frequency of the oscillator.

Because of this action, the plate current will vary or pulsate at the oscillator frequency and develop a-c power in the plate tank circuit which, in Figure 1, consists of coil L1 and condenser C1. This circuit may be tuned to the fundamental or some harmonic of the frequency to which the grid tank circuit L-C is tuned.

Through the inductive coupling between the coils, power in the plate tank circuit L1-C1 is carried over to coil L2 and radiated into space when the coil is connected in a suitable antenna system.

Notice in our explanation so far, there is nothing to cause a change in either the frequency or amplitude of the output. However, should we connect a telegraph key in the cathode circuit of the tube, the oscillator could be stopped and started at will to provide code transmission. We mention that action mainly to show that the high frequency output must be modulated in order to carry intelligible signals.

Going back to Figure 1, the greater the magnitude of the current changes in the load circuit, the greater the a-c power available for radiation of intelligence. In order to obtain greater power output, greater plate voltage changes are required. Consequently, the power output of this transmitter is controlled fundamentally by the magnitude of plate voltage changes.

Between the "B+" supply and the tuned plate circuit, "C1-L1" you will find the coil TS which is the secondary of an audio frequency transformer. Because of its series connection, any voltage developed in this winding will be impressed on the plate circuit of the oscillator tube.

For simplicity, we have shown the transformer primary winding, "TP" connected in series with a carbon microphone and a battery. When sound waves strike the microphone diaphragm, they cause it to vibrate and this movement produces a corresponding change in the resistance of the carbon button. As a result, the current in the circuit will vary at the frequency of the sound waves which strike the microphone diaphragm and the amount of this variation will be proportional to the strength of the sound.

The current changes in the primary of "TP" will cause corresponding changes of voltage across the secondary TS. Considering this voltage as a-c, during one alternation it will aid the d-c supply, causing the total plate voltage to increase and during the following alternation, it will oppose the d-c supply, causing the total plate voltage to decrease.

Because of this action, the strength, or amplitude of the oscillator output will vary with the sound waves which strike the microphone diaphragm, to produce what is known as amplitude modulation.

As explained in the lesson on resonant frequency circuits, the basic expression for resonance is $f = \frac{1}{2\pi\sqrt{LC}}$. Since there is no indication of "R" in the formula, changing the resistance of the circuit, containing an L-C tank, does not change the value of the resonant frequency, but rather changes the magnitude of the current in the circuit.

It is customary to represent the output of an amplitude modulated wave by the plan of Figure 2-B, and we want you to study it carefully in order to be familiar with two important characteristics.

First, as indicated by the light, broken vertical lines, the frequency of the oscillator remains constant as each cycle occupies the same horizontal distance on the curve.

Second, the height or amplitude of the cycles vary and, by drawing a light line across the tops or bottoms of each of the peaks of the cycles of Figure 2-B, the resulting curve would represent the modulation frequency or signal.

Thus, for amplitude modulation, the carrier has a constant frequency the amplitude of which varies as the signal or modulation frequency. Looking at Figure 1 again, you can see that the stronger the audio signal at the microphone, the greater the voltage across "TS". This, in turn, means a greater variation in the amplitude of the cycles of Figure 2-B.

At the left of Figure 2-B we show a few cycles of unmodulated output and you will notice both the frequency and output are constant. The heavy line directly above the left part of Figure 2-B labeled "no sound" (Figure 2-A) indicates further that no intelligence is carried by the wave. The curve at the right of Figure 2-A is the wave form of the modulating signal, and is a loud note of rather low frequency. The wave is really a projection of the variation in amplitude of Figure 2-B. Horizontal line "A" of Figure 2-B represents the axis or line of zero output and thus, the distance between lines A and B represents the value of the unmodulated output.

Following the peaks of the modulated cycles, you will find they drop from line B to line C and then rise from C to B to D. Thus, line B becomes the axis of the modulation frequency and the distance between lines C and B or D and B represents the amplitude of the signal frequency.

When the value of BD is equal to that of AB, the amplitude of the carrier will vary from zero to twice its unmodulated value and we say there is 100% modulation. For other values, the percentage of modulation is the ratio between the peak of the modulating frequency and the peak of the unmodulated carrier. Using the letters of Figure 2-B as an equation

$$\% \text{ modulation} = \frac{BD}{AB} \times 100$$

Figures 1 and 2 represent the common system of amplitude modulation and, as the action of receivers designed for this type of signal has already been explained in detail, we will not repeat.

FREQUENCY MODULATION

Earlier in this lesson we said that, "In general, the control of the radiated energy, enabling it to carry signals, is known as Modulation", but nothing was said in respect to the type of control. For code transmission, the carrier frequency is simply stopped and started at the desired instants, while for amplitude modulation, the strength of the carrier frequency is varied at the rate of the signal frequency.

To illustrate another method of modulation, for the circuit of Figure 3 we have the oscillator of Figure 1, but, instead of the carbon microphone and transformer in the plate circuit, have connected a condenser type microphone across the tuning condenser of the oscillator tank circuit.

However, as we mentioned for the circuit of Figure 1, the oscillator frequency is controlled by the values of C and L in the tank circuit. As L represents a coil of fixed inductance, the frequency can be adjusted by changing the capacity of the variable condenser "C".

Referring again to the familiar resonant frequency formula,

$$f = \frac{1}{2\pi\sqrt{LC}}$$

a change of the capacity "C" will change the value of the resonant frequency. As a matter of fact, increasing the value of C decreases the value of the resonant frequency, whereas decreasing "C" increases the frequency.

From the explanations of the earlier lessons, you will remember that the diaphragm of a condenser type microphone is in effect, the movable plate of a two plate variable condenser. The sound waves, which strike the diaphragm, cause it to deflect and this movement produces a corresponding change of capacity.

In the simplified arrangement of Figure 3, these variations of capacity in the microphone will cause a change in the total capacity across the tank coil L and thus produce corresponding change of oscillator frequency. With this arrangement, the audio or signal frequencies will control the oscillator or carrier frequency and thus we have Frequency Modulation.

The curve of Figure 4-B represents the modulated output of the oscillator of Figure 3, the same as the curve of Figure 2-B conforms to Figure 1. By comparing these two curves carefully, you will notice, in Figure 4-B the amplitude remains constant but the frequency, shown by the horizontal distance between adjacent peaks, has quite a wide variation.

In Figure 4-A the curve again shows the waveform of the audio modulating signal, and we will assume that it represents a note of low audio frequency of medium loudness.

As already explained, when no modulation exists a definite frequency will be generated as determined by the values of L-C in Figure 3. Under this condition the condenser microphone, will have a fixed value and added to C, will cause the oscillator to generate a "mean" frequency, sometimes called

the "center" frequency. Checking Figures 4-A and B, the mean frequency occurs when the a-c audio wave crosses its reference axis.

The curve of Figure 2-B represents a carrier of constant frequency with varying amplitude while the curve of Figure 4-B represents a carrier of constant amplitude with varying frequency. Keep this fundamental difference in mind because it is important.

Going back to the microphone of Figure 3, the diaphragm will vibrate at the frequency of the sound waves which strike it and its movement varies the oscillator frequency. Therefore, the oscillator frequency will vary at the rate of the signal frequency.

To keep the illustration simple we will assume that with no action of the microphone, the oscillator operates at a frequency of 1000 kc. Then, as sound waves of some fixed amplitude strike the microphone diaphragm, its movement one way increases the total capacity of the circuit just enough to reduce the oscillator frequency to 995 kc. At the other end of its travel, the diaphragm reduces the total capacity of the circuit by a similar amount and increases the oscillator frequency to 1005 kc.

Thus, each complete vibration of the diaphragm will cause the oscillator frequency to shift from 1000 kc to 995 kc, back through 1000 kc, up to 1005 kc and back to 1000 kc. From these values, you can see that each cycle of diaphragm movement causes one cycle of frequency changes in the oscillator, and the bandwidth required for transmission is 1005-995 or 10 kc.

For example, a 400 cycle sound wave will vibrate the diaphragm 400 times a second, therefore, the above frequency changes occur 400 times per second. A 1000 cycle sound wave will vibrate the diaphragm 1000 times a second, therefore, the frequency changes given above will occur again but, at the rate of 1000 times per second.

The important point to remember here is that each vibration of the diaphragm causes the same changes of oscillator frequency. Different signal frequencies produce different rates of diaphragm vibration and therefore, cause different rates at which the changes of oscillator frequency take place. 2

As we will explain later, the amount of frequency change, or deviation swing, is important but, at this time we want to emphasize only that the signal frequencies are transmitted by changing the rate at which the oscillator or carrier frequency is varied. 3

Going back to Figure 3, we will assume that a high amplitude sound wave strikes the microphone diaphragm, forcing it to move a greater distance. This will produce a greater change of microphone capacity which, in turn, will cause a greater change of oscillator frequency.

Continuing our former illustration, we will assume now that each complete vibration of the diaphragm will cause the oscillator frequency to shift from 1000 kc to 990 kc, back to 1000 kc, up to 1010 kc and back to 1000 kc. This is the same as the former cycle of frequency changes but, the greater movement of the diaphragm has caused a frequency shift of 1010 - 990 kc. Thus the carrier occupies a 20 kc band instead of the 10 kc band of our former explanation.

To illustrate this difference you can imagine that the curve of Figure 4B represents the 10 kc band width transmission while that of Figure 5B represents the 20 kc band. The curve of Figure 5A represents twice the amplitude of the curve of Figure 4A yet the audio signal has the same frequency because the audio variations provide the same variations of carrier frequency in the same length of elapsed time. Therefore, the only difference between Figures 4B and 5B is the deviation from the mean carrier, and 5B has twice the deviation of 4B. Remember for both of these curves, the frequency of the signal determines the rate at which the oscillator, or carrier frequency, swings through the band. In both cases, the oscillator output has constant amplitude. 2

For the curve of Figure 2B the strength of the signal determines the percentage of modulation which is a ratio between the peak value of the modulating frequency and the peak value of the non-modulated carrier.

For the curves of Figures 4B and 5B, the strength of the audio signal controls the amount of frequency variation and 3 the extent of modulation must be described in terms other than those of the amplitude modulated wave.

In general, when referring to a class of stations operating in the same service, a certain maximum frequency swing may be agreed upon as representing 100% modulation. In the case of f-m broadcast stations, a frequency swing of plus or minus 75 kc from the unmodulated center frequency is commonly considered as being 100% modulation.

MODULATION INDEX

However, a recent adoption of describing the extent of modulation lies in stating the value of the "modulation index" (M). This index is simply the ratio of the amount by which the transmitted frequency swings from its average frequency to the value of the modulating frequency.

For example, if the modulating frequency swings the transmitted frequency over the range of ∓ 5 kc, and the audio modulating frequency is 5000 cycles, the modulation index M is 5000/5000 or 1. Similarly, should the modulating frequency be 10,000 cycles, the index M is 5,000/10,000 or .5.

Note carefully that in describing the extent of frequency modulation, the modulation percentage and modulation index are defined in a different manner. Summarizing these points, the greater the magnitude of the modulating signal the greater the frequency swing, which means that the modulation percentage is directly proportional to the frequency swing.

If a frequency swing of ∓ 75 kc is considered 100% modulation, then a modulated carrier having a frequency swing of ∓ 37.5 kc would be modulated 50%.

The modulation index M is inversely proportional to the highest modulating frequency because, using the example cited above, the increase from 5000 to 10,000 cycles as the modulating frequency caused a reduction of the index M from 1. to .5.

As was explained in the lesson on Superheterodyne Receivers, it is possible to generate an output voltage which contains the sum and difference frequencies, as well as the original frequencies, when two different frequencies are combined. By higher mathematics it can be shown that the frequency modulated output is the sum of a center frequency and numerous pairs of sideband frequency components. The center frequency then is really the unmodulated carrier, and the two components of the first sideband pair have frequencies respectively higher and lower than the center frequency by the value of the modulating frequency, just as in amplitude modulation.

In frequency modulation, however, there are additional pairs of sideband components which have amplitudes great enough to be important

For example, there may be a second pair of sideband frequencies which have values higher and lower than the center frequency by twice the value of the modulating frequency. Likewise, a third pair of sideband frequencies may exist which are removed from the center frequency by three times the modulating frequency. Sideband frequencies of higher orders may be important too, but under certain conditions which will be explained, these frequencies may be neglected.

BESSEL FACTORS

Convenient tables have been compiled for determining the important sideband frequencies, and in table 1, at the end of the lesson, we show Bessel Factors for finding the amplitudes of center and sideband frequency components.

Column one represents the modulation index (M) from 0 to 6, the second column, J_o (M) with F just below, shows the relative value of the amplitude of the components of the f-m wave compared to an unmodulated carrier of 1, where F, the carrier frequency is designated. The columns J_1 (M) to J_9 (M) can best be explained by referring to an example.

Considering the case of modulating frequency of 10,000 cycles with a frequency swing of ∓5000 cycles, the modulating index (M) is 5,000/10,000 or .5. For an M of .5, J_o (M) is .9385, indicating the amplitude of the center frequency component is roughly 94% of the amplitude of the unmodulated carrier. The first pair of sidebands represented by column J_1 (M), with the frequencies being F + 10,000 cycles and F - 10,000 cycles, have an amplitude of .2423 or 24% of the carrier wave. The second pair of sidebands (J_2 (M) /F ∓ 2 F_M) as read opposite .5 in the M column is .0306 or approximately 3% of the amplitude of the f-m carrier. Notice here, F ∓ $2F_M$ is the frequency of the carrier ∓ 2 (10,000) or F ∓ 20,000 cycles.

The values for the third pair of sidebands (J_3 (M)) are not shown and the actual value is less than .005 or .5% of the amplitude of the carrier, and thus the sideband pair is not important.

F-M BAND WIDTH

The band width of an f-m wave depends upon the number of important sidebands as well as the modulating frequency. In the example just cited, two pairs of sidebands were important. The frequencies of the second pair differ from the center frequency by the greatest amount and hence determine what the band width will be. One of the sideband frequencies is higher than the center frequency by two times the modulating frequency of 10,000 cycles, and the other sideband frequency is lower by the same amount. 20,000 cycles above and 20,000 cycles below the center frequency gives an over-all frequency change of 20,000 + 20,000 or 40,000 cycles. Thus, 40 kc is the required band width.

To determine the band width required for an f-m transmission under other conditions, let's assume we desire to learn the band width of an f-m wave when the audio modulating frequency is 2000 cycles and the strength of modulation provides a frequency swing of ∓ 8 kc.

The modulation index (M) is 8000/2000 or 4. From table 1, under M = 4, read to the right and find .0152 under column J_7 (M). This data tells you that seven sidebands are important, the seventh sideband having 1.5% of the amplitude of the center frequency. The band width, however, is determined from

$F \mp 7F_M$, and as F_M = 2000 cycles, 7 F_M = 7 x 2000 = 14,000 cycles. Therefore, the upper sideband limit is 14 kc and the lower sideband limit is also 14 kc. The over-all deviation or band width is 2 x 14 kc or 28,000 cycles.

From the explanations given, and the examples shown, you can see that the band width of an f-m wave varies, and the accepted maximum limit of the sideband deviation is + 75 kc, or a band width of 150 kc, as stated in a previous section of this lesson.

The reason for the limit is not because of the nature of the radiated wave, but rather to characteristics of the transmitter.

F-M VS. A-M RADIATED POWER

You have already learned that the amplitude of an f-m wave is constant, and only the frequency varies with elapsed time. However, the average power during any r-f cycle is the same as for any other cycle in the transmission. Therefore, in order to maintain a constant power output when sideband currents appear, the amplitude of the center frequency must decrease sufficiently to keep the total "I^2R" product of all the components equal to the power of the unmodulated carrier.

The above action is in direct contrast with the condition in a-m waves. The radiated power from a carrier having amplitude modulation varies with the magnitude of the modulation. In other words, the power output of the circuit of Figure 1 varies with the audio modulating signal, whereas the power output of the circuit of Figure 3 remains constant and under conditions of f-m the amplitude of the center or carrier frequency varies with modulation.

Generally speaking, the power required for radiating an f-m wave is less than the power for the radiation of the same intelligence in an a-m wave. Such a feature is important from the standpoint of transmitter operation costs and efficiencies.

FREQUENCY MODULATION METHODS

The circuits of Figures 1 and 3 have been simplified, for the sake of illustration and cannot be considered suitable for practical operation. In the circuit of Figure 1 for example, audio modulation of the oscillator is not satisfactory as the changes of plate voltage cause undesired changes of the carrier frequency.

For the circuit of Figure 3, as frequency changes are desired, it is necessary to modulate the oscillator, but the frequency variation of the oscillator output would not be sufficient for satisfactory reception.

There are numerous methods of obtaining the amplitude modulated carrier of Figure 2-B, and in the same way, there are various methods of obtaining the frequency modulated carrier of Figures 4-B and 5-B. The simplified arrangement of Figure 3 illustrates what is known as "pure" frequency modulation and it is only the strength or amplitude of the signal which controls the swing or deviation of the oscillator frequency.

Another system makes use of the elements found in the Automatic Frequency control circuits used in some superheterodyne radio receivers. For frequency modulation, however, the control tube is made to work in reverse and vary the oscillator frequency according to the signal.

The method invented by Major Edwin Armstrong operates on a somewhat different principle, known as "Phase Modulation" to produce the variations of carrier frequency, and for the following explanation, we will assume that "Phase Modulation" is a form or method of Frequency Modulation. The over-all principle of operation is the generation of a fixed frequency carrier which provides frequency modulation when combined with an "out of phase" modulating signal.

7

PHASE MODULATION

Before trying to follow the action and purpose of the various units of a system of this kind, it will be well to review a few a-c principles and the methods of illustrating them.

Starting at the left of Figure 6, we have drawn the line "O-A" of a length to represent the maximum value of the a-c voltage of some circuit. This line is called a vector and may represent either current or voltage values.

However, a-c values are continually changing and therefore, we rotate the vector O-A around the center O and consider each complete revolution as one cycle. It is customary to consider the rotation in an anti-clockwise direction and thus, the horizontal, right hand position of the vector is considered as 0° or the beginning of the cycle.

Following around the circle from this point, we show 12 successive positions of the vector and have marked them in degrees as measured from the starting point. Adding 30° to the 330° position, you will see that the 360° and 0° positions are the same and, if the rotation is continued, the same variations will be repeated.

Also, you will remember that at 0° of a cycle, the a-c values are usually taken as zero, therefore, we extend the position of the 0° vector over to the right and consider it as a zero axis. If the vector rotates at a uniform speed it will move each 30° in equal time and, therefore, we divide the zero axis into twelve equal parts to represent this time.

Knowing that a-c values are zero at 0° or 180° and maximum at 90° or 270°, we let the vertical distance, between the outer end of the vector and the 0° or base line, represent the a-c value for that particular point or phase of the cycle.

To plot a curve of these changing a-c values, we first extend horizontal lines, from the outer end of the vector, in the various positions. Lines are then drawn vertically, from the divisions of the axis, and the points at which corresponding lines intersect, are points on the curve.

For example, from the end of the 30° position, a horizontal line is drawn to the right while a vertical line is drawn up from the 30° division of the axis. The point at which these lines cross, or intersect, is a point on the curve. Following this plan for all twelve divisions, we have 12 points and, joining them with a line, have a curve for one cycle. This, by the way is what we call a sine curve or sine wave.

The point we want to bring out at this time is the relationship between the vector and the curve. If we are concerned only with conditions at some particular instant or phase of a cycle, a vector, drawn of proper length and at the correct angle, will provide as much information as the curve. This is important because, when more than one a-c value is under consideration, complete curves become rather complicated while vectors, drawn properly as to length and position, can be made to serve the same purpose.

In Figure 7-A, for example, we show an oscillator and modulator voltage, both of the same frequency, but 90° out of phase. A modulator is essentially an a-f amplifier, but the name given it is more descriptive of its service. The oscillator vector is drawn vertically and the modulator vector drawn horizontally to provide the 90° angle between them. As both have the same strength or amplitude, both vectors are of equal length.

In order to add vectors, we simply complete a parallelogram, of which the vectors form two sides, and then draw in a diagonal. In Figure 7-A, the vectors are at an angle of 90° and

of equal amplitude, therefore, the parallelogram is a square and the diagonal, marked "Carrier", is a vector which represents the strength and phase angle of the combination of the original two. The original voltages were 90° out of phase but, being of equal amplitude, the resultant voltage is 45° out of phase with both.

For Figure 7-B, we again have the arrangement of Figure 7-A, except that the amplitude of the modulator has been reduced to 1/2 of its former value. Following the former plan, the resultant "Carrier" vector has been drawn in but it does not lie midway between the original vectors. Instead, it has shifted in phase by the angle "b".

For Figure 7-C, the modulator vector has been drawn to represent a value 1 1/2 times that of the oscillator. Following the former plan, we find the resultant vector has shifted in phase by the angle "C", compared to that of Figure 7-A.

Checking the three conditions of Figure 7, you can see that when two like frequencies are combined at a constant phase difference, a change of amplitude in one will cause a phase shift of the resulting voltage.

As shown in Figure 8, a similar phase shift is obtained when two like frequencies, of equal amplitude, are combined at different phase angles and Figure 8-A duplicates the conditions of Figure 7-A.

For Figure 8-B, the amplitude of the "Mod". vector remains equal to that of the oscillator but the angle between them is less than 90°. As a result, the carrier is shifted by angle "b" as compared to that of Figure 8-A.

By increasing the angle, between the "Osc" and "Mod" of Figure 8-C, to more than 90°, the phase shift through angle "C" is produced.

In general, therefore, we can state that two like frequencies of equal amplitude, when combined at a varying phase angle, cause a phase shift of the resulting voltage.

To show the action in a different way, for Figure 9 we have followed the plan of Figure 6 and rotated the "Carrier" vector of Figure 7-A through several cycles. The resulting curve is shown by the broken line which is marked "Unmodulated Carrier".

To reproduce the conditions of "B" and "C", Figure 7, we have drawn the "Modulated Carrier" curve of Figure 9 but, for simplicity have assumed both curves to have equal amplitude.

Starting over on the left, at point "A" we have the conditions of Figure 7-A and then, moving to the right, the modulated carrier curve falls behind until at point "B", we have the conditions of Figure 7-B.

Continuing to the right of Figure 9, we pass through another point A and then to point "C" where the conditions are those of Figure 7-C. In effect, therefore, the phase shift causes the modulated carrier to lag or lead the unmodulated carrier.

Starting at the left again, between points A and B, Figure 9, you will notice that a cycle of the modulated carrier occurs in a shorter horizontal distance than a cycle of the unmodulated carrier. As explained for Figure 6, the horizontal distance represents elapsed time and thus the modulated carrier cycle occurs in a shorter time than the unmodualted carrier cycle.

In electronics, frequency means the number of cycles per second or, as an equation

$$f = \frac{1}{t}$$

when

f = frequency in cycles per second
t = time of one cycle, in seconds

Going back to Figure 9, and keeping this equation in mind, if one cycle of the modulated carrier occurs in a shorter time, its frequency must be higher than that of the unmodulated carrier.

Between points B and C of Figure 9, the modulated carrier cycles require a greater time and thus the frequency is lower than that of the unmodulated carrier. Notice also, at points "A" which can be thought of as zero modulation, there is zero phase shift and the frequency of both curves is the same.

Thus, a change of amplitude or phase, of the modulation, as shown in Figures 7 and 8, causes a phase shift in the resultant carrier and in Figure 9, you can see that this phase shift corresponds to a change of frequency. The final result therefore is similar to that explained for the simplified circuit of Figure 3.

GENERAL REQUIREMENTS

Major Armstrong lists two basic requirements of a Frequency Modulated Transmitter as,

1. "The frequency transmitted by an f-m system should vary alternately above and below a fixed frequency which is the assigned carrier. These variations should be symmetrical with respect to the said frequency, pass through it and return exactly to this carrier when modulation stops."

2. "In the transmitter, the frequency deviation of the f-m wave at any instant must be directly proportional to the intensity of the modulating current resulting from the program. This deviation in frequency, however, must be independent of the frequency of this modulating current."

MAJOR ARMSTRONG'S SYSTEM

To meet the requirement of a fixed carrier frequency, Major Armstrong employs a crystal controlled oscillator of the type commonly used by amplitude modulation systems. However, this frequency must be varied according to the signal and, for Figure 10, we have a simplified sketch of Major Armstrong's system. 8

Starting at the left, the crystal controlled oscillator output is divided into two parts, one of which passes into the upper amplifier and the other into the balanced modulator.

The audio signal is picked up in the usual way, by means of a microphone, the output of which passes through a correction network so that the signal voltage is inversely proportional to its frequency. In any system of Radio Transmission, the high frequencies are attenuated most and by making the proper correction at this point, it is possible for the receiver to reproduce all signal frequencies with more uniform amplitude.

The corrected signal frequencies, marked "Audio Input" on Figure 10, are also fed into the balanced modulator and mixed with the oscillator frequency. Because of its balanced circuit, the modulator output does not contain the oscillator frequency but only the combinations of oscillator and signal frequencies which are considered as the "sidebands" of the carrier. In the heterodyne principle, combining two waves produces sum and difference frequencies. The removal of the carrier of a modulated wave leaves the sum of the sideband components which are sometimes called the double sidebands. These sideband frequencies are then shifted in phase by 90° and mixed with the output of the oscillator amplifier, to provide frequency modulation.

Thinking of the oscillator and phase shifter outputs as being of equal amplitude, the conditions of Figure 8 are present in effect because the varying frequencies of the sidebands will cause a variation in the 90° angle between them and the oscillator frequency.

The action here, as already explained, will cause a phase shift and frequency change of the resulting voltage. At this point, however, the actual frequency change is quite small and for a 200 kc oscillator, the deviation is about 15 to 20 cycles.

Going back to Figures 3, 4 and 5, the deviation in frequency is proportional to the amplitude of the signal while in the f-m receiver the deviation in frequency is converted into corresponding changes of amplitude. To provide proper receiver operation and satisfactory signal to noise ratio, the deviation of Figure 10 must be greatly increased.

Yet is is not practical to provide an initial frequency deviation such that the sideband amplitude is made greater than about 1/5 the amplitude of the carrier. To exceed this value introduces amplitude variations which are undesirable, and the phase deviation will no longer be proportional as determined by the amplitude of the modulating voltage. Thus only a slight frequency shift should be produced in the phase shift modulator.

FREQUENCY DEVIATION MULTIPLICATION

To overcome these limitations it is common practice to employ a low frequency crystal oscillator followed by frequency multipliers which increase the frequency deviation as well as the carrier or mean frequency.

Most oscillators produce harmonic frequencies, in addition to the one to which they are tuned. The tuned frequency is the "Fundamental" and two times the Fundamental is the "Second Harmonic", three times the fundamental, the "Third Harmonic" and so on.

A simple Frequency Doubler is usually a stage or arrangement in which the input circuit of a tube is tuned to the fundamental frequency while the output circuit is tuned to the second harmonic. For a "Tripler", the output circuit is tuned to the third harmonic.

Compared to the earlier experiments in Frequency Modulation in which an effort was made to reduce the bandwidth, Major Armstrong's system employs a bandwidth of approximately 150 kc. This, you will notice is very wide in respect to the 10 kc band of the amplitude modulated Broadcast signal.

DOUBLER STAGES

To obtain this broad band, from the small frequency deviation explained for Figure 10, the signal is passed through a number of doubler stages. You can think of these as stages which amplify the frequency deviation.

For example, if the output of Figure 10, with a 20 cycle deviation, is passed through 13 doubler stages, the final output will have a deviation of over 160 kc. As the operation of a doubler stage is not critical, the f-m transmitter includes a sufficient number to provide the necessary deviation.

In order to obtain distortionless modulation from a phase shift modulator, the maximum phase deviation of the f-m voltage at the output should not exceed .2 radian. The term "radian" is really another method of measuring angles, and turning to Figure 6, the 360° of the circle form 2π radians Dividing 360° by 2π (6.28) results in a value of about 57° for each radian. Therefore, .2 of a radian is $.2 \times 57^{\circ}$ or about 11.4°.

In Figure 9 we have indicated the radian displacement of the modulated and unmodulated carrier although the drawn displacement of these two waves is greater than allowable in actual circuits.

It may be believed that multiplication of the deviation could go on and on, but there is a practical limit and the accepted ratio of the maximum frequency deviation of the transmitter output wave to the highest modulating frequency is 5 to 1.

For example, in f-m broadcast service, the maximum frequency deviation is 75 kc for the highest a-f modulating frequency or 15,000 cycles, and this is equivalent to a modulation index of 75,000/15,000 or 5. or a maximum phase deviation of 5 radians.

If the lowest modulating frequency is 50, the modulation index is 75,000/50 = 1500, equivalent to a phase deviation of 1500 radians. From this data, it can be shown that the required frequency deviation multiplication, in order to raise the .2 radian phase shift at the phase-shifter to 1500 radians at the output of the transmitter, is 1500/.2 or 7500.

Here again, using doublers, 13 doubler stages would be required because 2^{13} (2 x 2 x 2 -- thirteen times) results in 8,192. Of course, other arrangements or doubler and tripler stages could be employed to achieve the desired multiplication.

F-M PROPAGATION

The present f-m station channel width is 200 kc, while the a-m broadcast station occupies a band width of 10 kc. It is easy to see that but few 200 kc channels could be allocated in the standard Broadcast band. Commercial f-m stations have been assigned a special band of transmitting frequencies above 80 mc.

As both a-m and f-m propagation require the same medium, it would be well to review the Lesson on Antennas in order to recall the behavior of electromagnetic waves in space. It is known the ionized layer (E, F_1 and F_2) contain comparatively large numbers of free electrons and thus have the property of refracting radio waves. Whether or not the wave will be bent back to the earth depends on the frequency of the wave, the height of the refracting layer, and its density of ionization.

In general, the waves of a-m stations in the Broadcast band are reflected, whereas the f-m waves above 30 - 40 mc penetrate the ionized layers and are not returned to earth.

As previously stated, the sky wave of a-m broadcast stations is predominate at night, and considering only the ground wave, the field strength at a receiving point remote from the transmitter depends upon the loss sustained by the wave. The amount of this loss depends upon the distance traveled, the conductivity of the earth, and the frequency of the transmitted wave. Of these factors, we are primarily concerned with the frequency of the wave, and field tests have indicated that the strength of the a-m wave decreases as the frequency increases. Therefore, the higher frequency of an f-m wave will have less "coverage".

High frequency waves have the property of traveling in straight lines, much like light, and therefore, are often called "Quasi-Optical". In general, a receiver should be within the "line of sight" coverage of a transmitter for satisfactory reception of f-m signals, although tests have shown it is possible to provide good signal strength at distances greater than twice the "line of sight" when the radiation power of the f-m station is relatively great. This is possible partly due to the wave following the curvature of the earth.

A condition which very often occurs, particularly at high frequencies, is the creation of a "shadow" area. This is the reduction of signal strength behind an object which is large enough to reflect the initial wave. Shadow areas become more noticeable as the frequency of the wave is increased. However, such conditions are partially corrected by erecting the f-m transmitter antenna relatively high and designing the antenna array for the purpose of concentrating the radiated power toward the horizon.

INTERFERENCE CONSIDERATIONS

Satisfactory reception not only depends upon sufficient signal strength but also on the exclusion of signals which spoil the program of the desired station. In a-m transmission of the Broadcast band, the ratio of the desired signal to the

undesired signal must be about 100 to 1 for good reception, whereas a ratio of 2 to 1 is adequate in an f-m system. As the maximum range of f-m stations is approximately the same during daytime and nighttime, it is possible to operate many more f-m stations on the same frequency with less geographical separation between stations than in the case of a-m stations.

The use of f-m at very high frequencies offers a solution fo the serious interference problem encountered in a-m broadcasting. Even the reduction of a-m power at sunset, 40 kc separation of local stations, and the use of directional antennas does not reduce the a-m interference conditions to a satisfactory level.

FREQUENCY ALLOCATIONS

It is indeed fortunate that we have such a body as the Federal Communication Commission to regulate the character of radio communication. There are many "classes of transmission" such as — "Transoceanic", "Ship to Shore", "Ship to Ship", "Navigation", "Government", "Aircraft", "Broadcasting", "Television", "Amateur", "Meteorological", "Non-Government and Government fixed and mobile transmissions", as well as experimental services.

It has been quite a task for the FCC to allocate suitable frequencies for all these services in the Radio Spectrum. For the present, new f-m transmission will be located in the band of frequencies extending from — 88 to 108 megacycles.

The term f-m broadcast "channel" means a band of frequencies 200 kc wide and is designated by its center frequency. Channels for f-m broadcast stations begin at 88.1 mc and continue in successive steps of 200 kc to and including 107.9 mc.

The "term service" area as applied to f-m broadcasting means that service resulting from and assigned effective radiated power and antenna height above average terrain.

Although some service is provided by reflected waves, the service area is considered to be only that served by the ground wave. The extent of the service is determined by the point at which the ground wave is no longer of sufficient intensity to provide satisfactory broadcast service. For city business or factory areas, the field intensity should be 1,000 microvolts per meter. For rural areas the field intensity considered necessary for service should be 50 microvolts per meter.

The Federal Communication Commission have set up certain standards of good engineering practice and these will necessarily be revised from time to time as progress is made in the art. The commission will accumulate and analyze engineering data available as to the progress of the art so that these standards may be kept current with technical developments.

The assignment on Frequency Modulation Receivers will explain the basic fundamentals involved in the reception of signals using f-m systems of transmission.

TABLE 1

BESSEL FACTORS FOR FINDING AMPLITUDES OF CENTER AND SIDEBAND FREQUENCY COMPONENTS

M	J_0 (M) F	J_1 (M) $F \pm F_M$	J_2 (M) $F \pm 2F_M$	J_3 (M) $F \pm 3F_M$	J_4 (M) $F \pm 4F_M$	J_5 (M) $F \pm 5F_M$	J_6 (M) $F \pm 6F_M$	J_7 (M) $F \pm 7F_M$	J_8 (M) $F \pm 8F_M$	J_9 (M) $F \pm 9F_M$
0.0	1.000									
0.1	.9975	.0499								
0.2	.99	.0995								
0.3	.9776	.1483	.0112							
0.4	.9604	.196	.0197							
0.5	.9385 94%	.2423 24%	.0306 3%							
0.6	.912	.2867	.0437							
0.7	.8812	.329	.0589	.0069						
0.8	.8463	.3688	.0758	.0102						
0.9	.8075	.4059	.0946	.0144						
1.0	.7652	.4401	.1149	.0196						
1.2	.6711 .6	.4983	.1593	.0329	.005					
1.4	.5669	.5419	.2073	.0505	.0091					
1.6	.4554	.5699	.257	.0725	.0150					
1.8	.3400	.5815	.3061	.0988	.0232					
2.0	.2239 22%	.5767	.3528	.1289 3	.034	.007 5				
3.0	-.2601	.3391	.4861	.3091	.1320	.0430	.0114			
4.0	-.3971	-.066	.3641	.4302	.2811	.1321	.0491	.0152		
5.0	-.1776	-.3276	.0466	.3648	.3912	.2611	.131	.0534	.0184	
6.0	.1506	-.2767	-.2429	.1148	.3576	.3621	.2458	.1296	.0565	.0212

F represents the carrier or mean frequency
F_M represents the audio frequency

To find the amplitude of any sideband pair, enter the table with the modulation index M, read the amplitude factor for the sideband pair and multiply the factor by the amplitude of the unmodulated carrier. The amplitude of the center frequency component is found in the same manner, taking the factor from the J_0(M) column.

Where no value is given, the actual value is less than .005 and the sideband pair is not important.

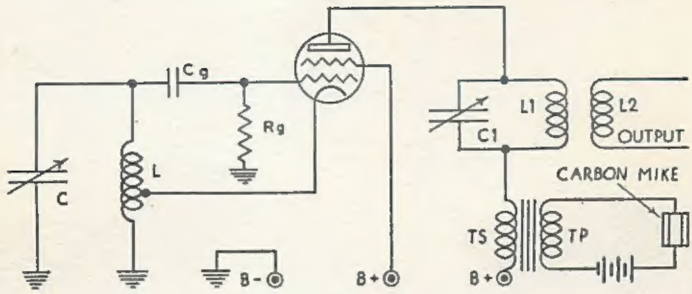

FIGURE 1

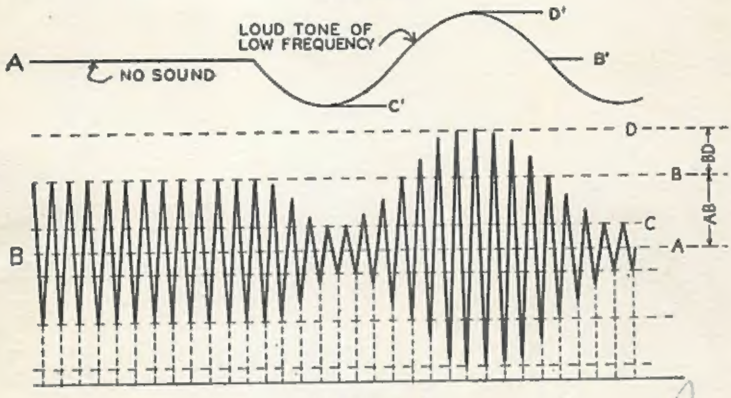

FIGURE 2

Jan-12th/1951

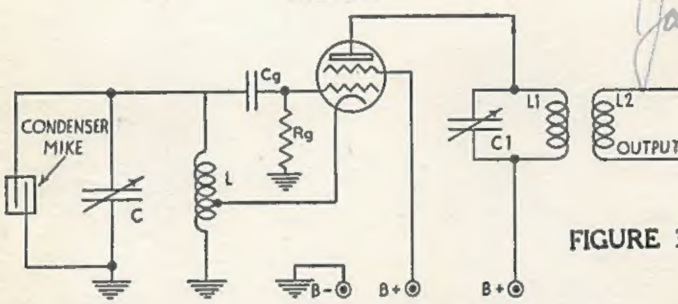

FIGURE 3

Jan. 12th/1951

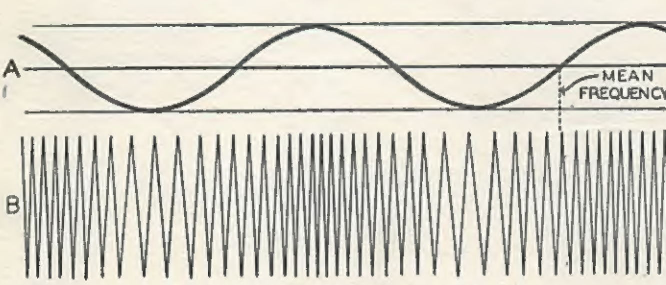

FIGURE 4

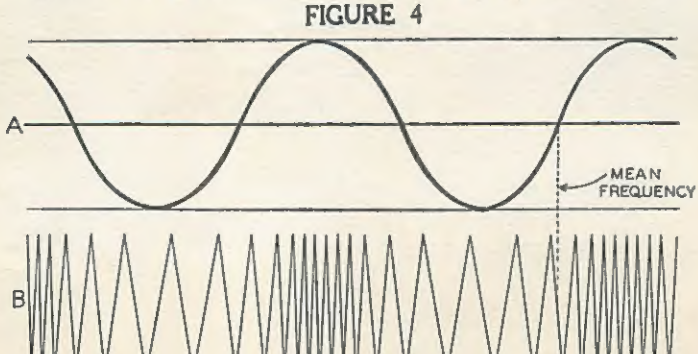

FIGURE 5

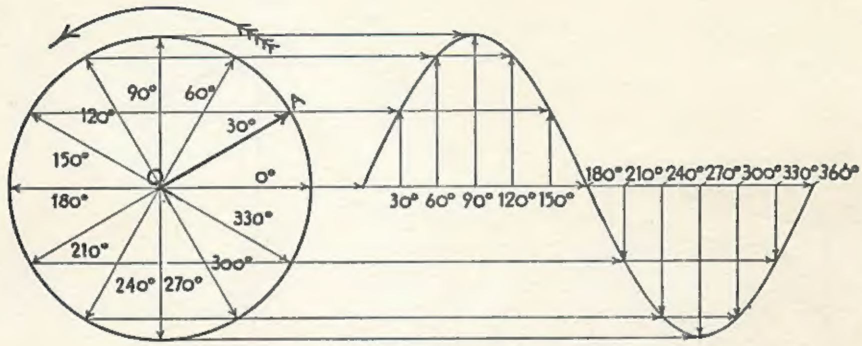

FIGURE 6

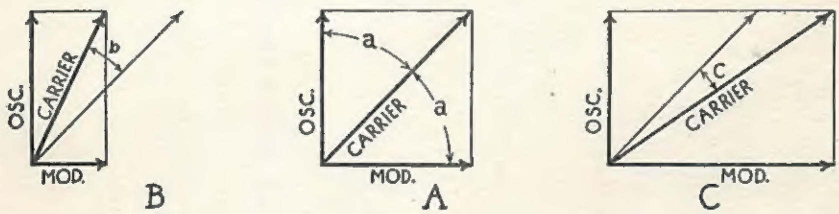

FIGURE 7

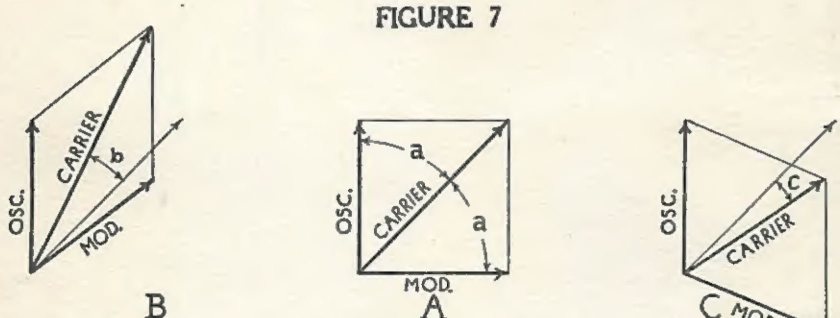

FIGURE 8

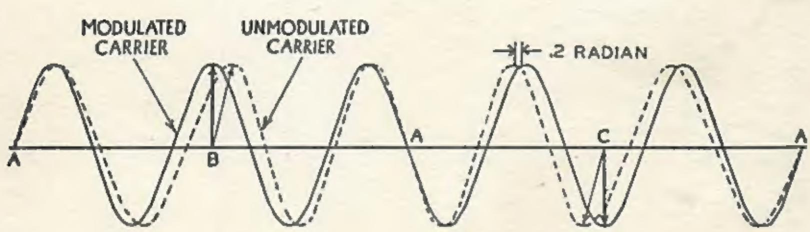

FIGURE 9

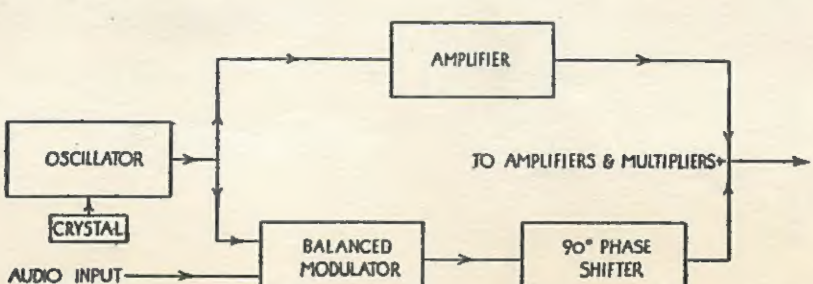

FIGURE 10

QUESTIONS AND ANSWERS

1. What is meant by "Frequency Modulation"?
Frequency Modulation is a form of modulation whereby sound signals control the frequency of the carrier.

2. In f-m systems, what controls the rate of change of the carrier frequency?
The rate of change is controlled by the frequency of the modulating signal.

3. In f-m systems, what controls the amount of frequency deviation?
The amplitude of the modulating signal controls the amount of frequency deviation.

4. (a) What is the modulation index of an f-m modulation system in which the frequency deviation is 10 kc and the audio modulating signal is 5000 cycles? (b) From Table 1, how many pairs of side bands are important?
(a) Modulation index = 10,000/5,000 = 2.
(b) From column J5, 5 side band pairs are important.

5. What band width will be required for the transmission of an f-m signal when the modulation index is 1 and the audio modulating signal is 4000 cycles?
From Table 1, there are 3 important pairs of side bands. The greatest deviation will be 3FM or 3 x 4000 = ±12000 cycles. As the band width is 2 times the deviation, the required band width is 2 x 12000 or 24 kc.

6. In an f-m system of electromagnetic wave propagation, does the transmitter output vary or remain constant under conditions of audio modulation?
In f-m transmission, the output power remains constant.

7. What is meant by "Phase Modulation"?
Phase modulation is a form of f-m which causes the generation of a fixed carrier frequency and provides f-m when combined with an out-of-phase modulating signal.

8. In the Armstrong method of phase modulation, why is a crystal controlled oscillator employed?
The oscillator is crystal controlled in order to maintain a fixed mean frequency of the carrier.

9. What causes undesirable amplitude variations in a phase shift modulator?
Excessive deviation introduces undesirable amplitude variations and does not permit proportional frequency changes as determined by the modulating signal. In effect, both factors are distortion.

10. What deviation multiplication is required to raise a .2 radian phase shift at the phase-shifter to 1200 radians at the output of the transformer?
Multiplication = $\frac{1200}{.2}$ = 6000